Numerical Techniques and Cloud-Scale Processes for High-Resolution Models

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LONG-TERM GOALS

The long-term goal of this project is to design and evaluate the components that will comprise a next generation mesoscale atmospheric model within the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[11]). It is anticipated that in order to meet future Navy requirements, next generation approaches to numerical techniques and physical parameterizations will be needed.

OBJECTIVES

The objectives of this project involve the development, testing, and validation of: i) new numerical techniques such as advection schemes and time differencing methods, and ii) new methods for representing cloud-scale physical processes. Both of these objectives are tailored to address high-resolution applications for horizontal grid increments at 1 km or less.

APPROACH

Our approach is to follow a methodical plan in the development and testing of a nonhydrostatic microscale modeling system that will leverage the existing COAMPS and new model prototypes. Our work on numerical methods will involve investigation of spatial and temporal discretization algorithms that are superior to the current generation leap-frog, second-order accurate numerical techniques presently employed in COAMPS and many other models; these new discretization methods will be developed and implemented. Our work on the physics for the next-generation COAMPS will feature the development of physical parameterizations specifically designed to represent cloud-scale processes operating on fine scales. A parameterization is proposed that properly represents the coupled nature between the turbulence and microphysics in droplet activation, evaporation, and auto-conversion processes for mesoscale and microscale models. Validation and evaluation of the modeling system will be performed using datasets of opportunity, particularly in regions of Navy significance.

WORK COMPLETED

1. Development of a turbulence-based cloud droplet activation parameterization.

We developed a framework for parameterization of cloud droplet activation in a high resolution mesoscale model. There are two key elements in the parameterization. First, the activation rate is a

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strong function of the turbulence intensity represented by the turbulence probability density function (PDF). Second, the activation depends on the activation time scale that is defined as the time required for a parcel to reach the level of maximum supersaturation from the cloud base. This time scale is a function of vertical velocity and CCN spectrum. Therefore, the new activation parameterization framework is closely coupled to the turbulence structure. We included this parameterization in a single column high-resolution turbulence closure model and tested the performance against DYCOMS (Dynamics and Chemistry of Marine Stratocumulus Cloud Experiment II) observations.

2. Spectral element and discontinuous Galerkin 2D prototypes.

Spectral element (SE) (see Giraldo 2005) and discontinuous Galerkin (DG) (see Giraldo 2006) methods are a new class of spatial discretization methods that are used to approximate the derivatives of the governing equations. In COAMPS and WRF, presently this is done using the finite difference method. The advantage of SE and DG methods is that they offer high-order accuracy (unlike low order finite differences) and this accuracy can be achieved on any unstructured grid – this is not true for finite difference methods where the differencing stencils require a certain level of structure (such as orthogonality). Based on SE and DG methods, we developed 5 different prototypes for the nonhydrostatic Euler equations. The goal of this exhaustive study was to determine not only which method to use for a next-generation model but also to determine which set of equations should be used. For example, currently in the literature at least three different forms of the Euler equations can be found. The first set we denote as set number 1 and is written as follows:

$$
\begin{aligned}
\frac{\partial \pi}{\partial t} &= -\bar{u} \bullet \bar{\nabla} \pi - \frac{R}{c_v} \pi \bar{\nabla} \bullet \bar{u} \\
\frac{\partial \bar{u}}{\partial t} &= -\bar{u} \bullet \bar{\nabla} \bar{u} - c_p \theta \bar{\nabla} \pi - g\bar{k} \\
\frac{\partial \theta}{\partial t} &= -\bar{u} \bullet \bar{\nabla} \theta
\end{aligned}
$$

where terms with a bar denote vector quantities. Equation set 1 is the form currently used in many mesoscale models, including COAMPS. This set is quite popular because it is completely self-contained; meaning that there are three equations and three independent variables with no equation of state required to close the system. The solution variables in this case are exner pressure (π), velocity (u), and potential temperature (θ). This equation set does not formally conserve mass and for this reason it makes little sense to either write the equations in flux-form or to use conservative methods to solve them. For example, this equation set is ideally suited for either finite difference or finite element methods which conserve mass only in a global sense.

A set that is becoming increasingly popular is set number 2 which is written as:

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\overline{\nabla} \bullet \left(\rho \overline{u} \right) \\
\frac{\partial \rho \overline{u}}{\partial t} &= -\overline{\nabla} \bullet \left(\rho \overline{u} \otimes \overline{u} + P \overline{I}_2 \right) - \rho g \overline{k} \\
\frac{\partial \rho \theta}{\partial t} &= -\overline{\nabla} \bullet \left(\rho \theta \overline{u} \right)
\end{aligned}
$$

where solution variables are density (ρ), momentum (ρu), and potential temperature (ρθ); however, in this form of the Euler equations there are three equations and 4 unknown variables (ρ, u, θ, and pressure). Thus in this case an equation of state is required to close the system. It is important to note that this form of the Euler equations is written in flux-form (conservation form) and that the variables are in fact conserved quantities. Therefore, for this equation set it makes perfect sense to use locally conservative methods such as finite volume or discontinuous Galerkin methods.

The equation set number 3 studied is the following:

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\overline{\nabla} \bullet \left(\rho \overline{u} \right) \\
\frac{\partial \rho \overline{u}}{\partial t} &= -\overline{\nabla} \bullet \left(\rho \overline{u} \otimes \overline{u} + P \overline{I}_2 \right) - \rho g \overline{k} \\
\frac{\partial \rho e}{\partial t} &= -\overline{\nabla} \bullet \left[\left(\rho e + P \right) \overline{u} \right] - \rho g \overline{u} \bullet \overline{k}
\end{aligned}
$$

where the conservation variables are density (ρ), momentum (ρu), and total energy (ρe); this is the set that is typically used in computational fluid dynamics (CFD). This set is also written in conservation form where all the variables are conserved quantities. While this set has been very popular in CFD, it is not so useful for geophysical fluid dynamics since most parameterization packages are written in terms of (virtual) potential temperature and not total energy. While we developed very accurate models using this equation set, we eliminate it from further consideration due to the difficulty of having to convert from total energy to potential temperature between the dry dynamics and moist physics.

3. Weighted Essentially Non-Oscillatory (WENO) methods.

Atmospheric models require numerical methods that can accurately represent the transport of tracers with steep gradients, such as those that occur at cloud boundaries or the edges of chemical plumes. In atmospheric sciences, the most widely used numerical techniques for this type of problem are flux-corrected transport or closely related flux-limiter methods. The limiters are typically designed to prevent the development of new extrema in the concentration field. This will preserve the non-negativity of initially non-negative fields, which is essential for the correct simulation of cloud microphysics or chemical reactions. One serious systematic weakness of flux limiter methods is that they also tend to damp the amplitude of extrema in smooth regions of the flow, such as the trough of a well-resolved sine wave. To avoid this problem, we have been investigating the application of WENO (Weighted Essentially Non-Oscillatory) methods to tracer transport in atmospheric models. WENO methods are widely used in many disciplines, but scarcely been tested in atmospheric applications. WENO methods preserve steep gradients while simultaneously avoiding the dissipation of smooth extrema by estimating the value of the solution in a way that heavily weights the smoothest possible cubic polynomial fit to the local function values. Where the solution is well resolved, all possible cubic interpolants are weighted almost equally. Near a steep gradient, those interpolants that straddle the gradient are almost completely ignored.

RESULTS

1. Development of a turbulence-based cloud droplet activation parameterization.

Figure 1a shows the dependence of the activation time scale on the vertical velocity and CCN spectrum. It ranges from 1.3 minutes for the marine spectrum and weak updrafts to just 8 seconds for the continental and strong updrafts. The time scale is shorter for a stronger upward motion because it provides more adiabatic cooling; and it is longer in a marine air environment (lower CCN number) since the supersaturation level is higher and the condensation rate is lower than those in continental air mass (higher CCN number). The turbulence closure model with the activation parameterization is used to simulate the vertical distribution of cloud droplet number and mean radius observed in DYCOMS2 field experiment. The modeled droplet number concentration and turbulence variables agree well with the observations. Our simulations suggest that the new parameterization should be applicable to next generation high resolution COAMPS where turbulence PDF may be well predicted or diagnosed.

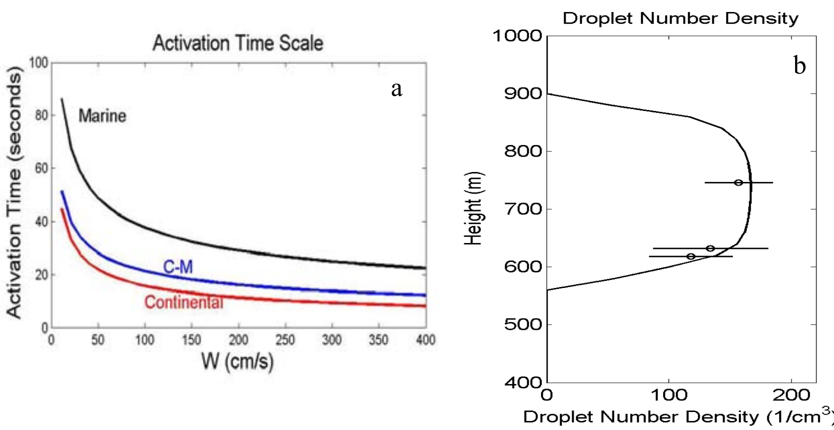


Figure 1. (a): Activation time scale as a function of upward velocity and CCN spectrum. The different CCN spectrum used in the calculation is denoted by "Marine", "Continental", and "C-M" (the mixed air mass) respectively; (b): Vertical profile of simulated cloud droplet number density. The circles are leg averages of aircraft data taken in DYCOMS flight 1; and horizontal bar is the scatter of the data.

2. Spectral element and discontinuous Galerkin 2D prototypes.

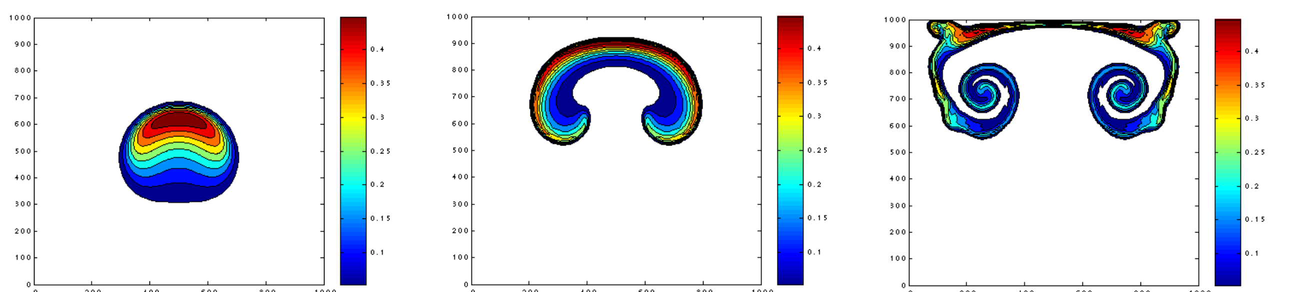
In order to determine which equation set along with which numerical method is best suited for building a next-generation mesoscale model, we ran simulations for two standard test cases. The test cases selected were the rising thermal bubble problem made famous by Andre Robert and the linear hydrostatic mountain wave used by Durran, Klemp, Skamarock, and analyzed in detail by Ron Smith. We used the spectral element and discontinuous Galerkin methods to solve the equations. We only show results for the SE method because both methods yield very similar results for these two particular test cases. However, it is expected that for more challenging problems (i.e., those having very steep gradients) the DG method should prevail.

The time-integrators used to advanced the models are a family of strongly stability preserving (SSP) schemes which are sometimes referred to as TVD time-integrators (TVD= total variation diminishing). These time-integrators control unwanted spurious oscillations near large gradients and when used in combination with slope limiters with the DG method results in a truly TVD method in both space and time. The TVD property is important because it means that the models never produce unphysical extrema throughout the time-integration regardless of the strength of the gradients. These methods have not been used previously in atmospheric models and we use a family of 2nd and 3rd accurate SSP methods.

2a. Rising thermal bubble.

The rising thermal bubble problem does not have an analytic solution since it involves the full nonlinear equations but is nonetheless a useful test because the solution is intuitively straightforward to understand. Another attractive trait of this problem is that the boundary conditions are quite simple since they only require no-flux across the domain boundaries which gives a good measure of how the discrete operators are behaving.

Figure 2 shows the color contours for the potential temperature perturbation from the isothermal reference state after 600 seconds. The result shown was obtained with the spectral element model using equation set one; however, this result is identical for all three equation sets using either the SE or the DG method. The initial thermal perturbation is a cosine wave with maximum of 0.5 above the reference state. Note that the color contours seen in Figure 2 are between 0 to 0.5 which shows that the model does not produce spurious extrema (overshoots or undershoots). In addition, the solution is very symmetric about the x=500 meter axis which is what one would expect.

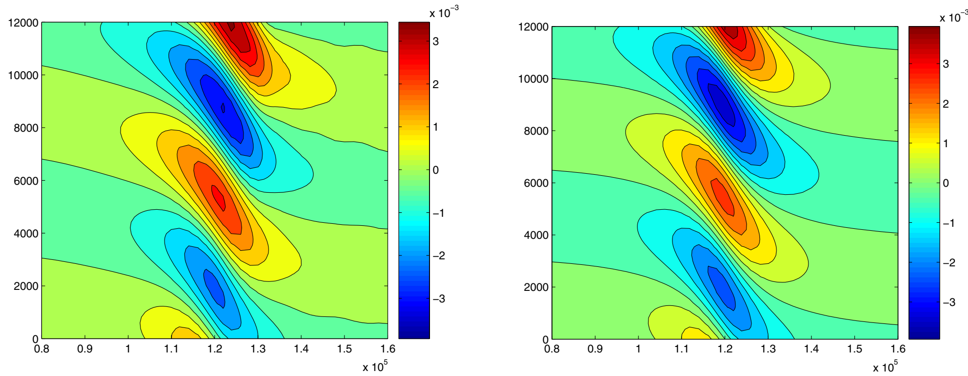


a) solution at 300 seconds ***b) solution at 600 seconds*** ***c) solution at 900 seconds***

Figure 2: The potential temperature perturbation from the isothermal reference state after a) 300, b) 600, and c) 900 seconds for the spectral element and discontinuous Galerkin nonhydrostatic models using a grid of 160x160 grid points in a 1 km x 1 km domain.

2b. Linear hydrostatic mountain waves.

The linear hydrostatic mountain wave problem, on the other hand, has an analytic solution which allows us to discuss quantitatively the performance of specific models. The main issue with this test case is that it requires more sophisticated boundary conditions (such as either non-reflecting/radiative boundary conditions or sponge layers) in order to properly perform the simulation. In the end, the accuracy of the simulation is completely determined by the quality of the lateral and top boundary conditions. Sophisticated radiation boundary conditions, while useful for this test case, unfortunately are not so useful in an operational setting where a global model is used to drive the boundary conditions of the mesoscale model.



a) Spectral Element Solution ***b) Analytic Solution***

Figure 3: The vertical velocity for the linear hydrostatic mountain wave after 10 hours for a) the spectral element model and b) the linear hydrostatic analytic solution. The simulation uses 160 x 160 grid points for a 240 km x 30 km domain.

Figure 3 shows the contours for the vertical velocity after a 10 hour simulation for the linear hydrostatic mountain with a height of one meter and half width of 10 kilometers. The numerical solution is shown on the left panel and the analytic solution on the right.

Defining the root-mean-square (RMS) error as follows:

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{N_P} \left(q_i^{\,N} - q_i^{\,A}\right)^2}{N_P}}$$

where the superscripts N and A denote the numerical and analytic solutions, and Np is the number of grid points, we compute the RMS error for the vertical velocity to be $1.09\text{x}10^{-4}$ which is extremely competitive with the results obtained with WRF and COAMPS.

3. Weighted Essentially Non-Oscillatory (WENO) methods..

The following three figures illustrate how WENO methods can perform in an atmospheric context involving trapped mountain lee waves. Fig. 4 shows the isentropes of potential temperature and the vertical velocity field (color fill) in simulations using numerical models that differ only in their treatment of potential temperature and passive tracer transport. In the top panel (a) , the WENO method is used for the advection, in the middle panel (b) leapfrog time, centered 4th-order spatial difference is used, and in the bottom panel (c) a flux limiter method proposed by LeVeque is employed. The leapfrog scheme is non-damping and correctly produces a large amplitude lee-wave. The WENO method gives essentially the same solution as the leapfrog scheme, but the flux-limiter method is incorrectly damped.

Now consider a complimentary test in which a passive tracer with uniform concentration of 1.0 is initially distributed throughout a rectangular region upstream of the waves. There are sharp gradients at each edge of the distribution, as shown in Fig. 5. As this tracer advects downstream, it is distorted by the shear and curvature in the wind field, but its edges should remain sharp and it should remain between the two isentropes that initially passed above and below it. As apparent in Fig. 6, the leapfrog scheme (panel b) is not capable of handling the steep gradients in the tracer distribution and creates a series of undershoots and overshoots. On the other hand both the WENO and the flux-limited methods perform well, with the WENO method preserving steeper gradients than the flux limiter method.

These tests show that the WENO method is capable of performing well in both situations (smooth flow with important extrema, and tracer transport with steep gradients), whereas each of the other methods only works well one of the cases.

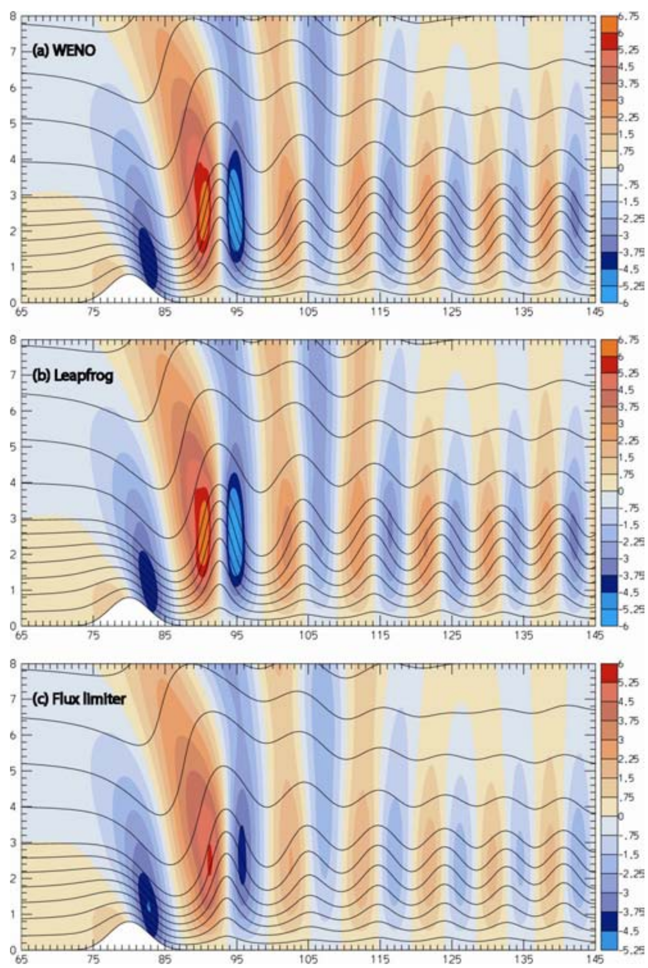


Figure 4. Isentropes and the vertical velocity field (color fill) for (a) WENO method is used for the advection, (b) leapfrog time, centered 4th-order spatial difference, and (c) a flux limiter method proposed by LeVeque.

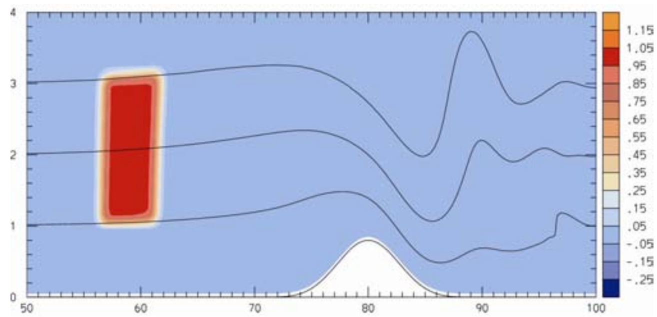


Figure 5. Initial passive tracer distribution with uniform concentration of 1.0 as represented by the rectangular region upstream of the waves.

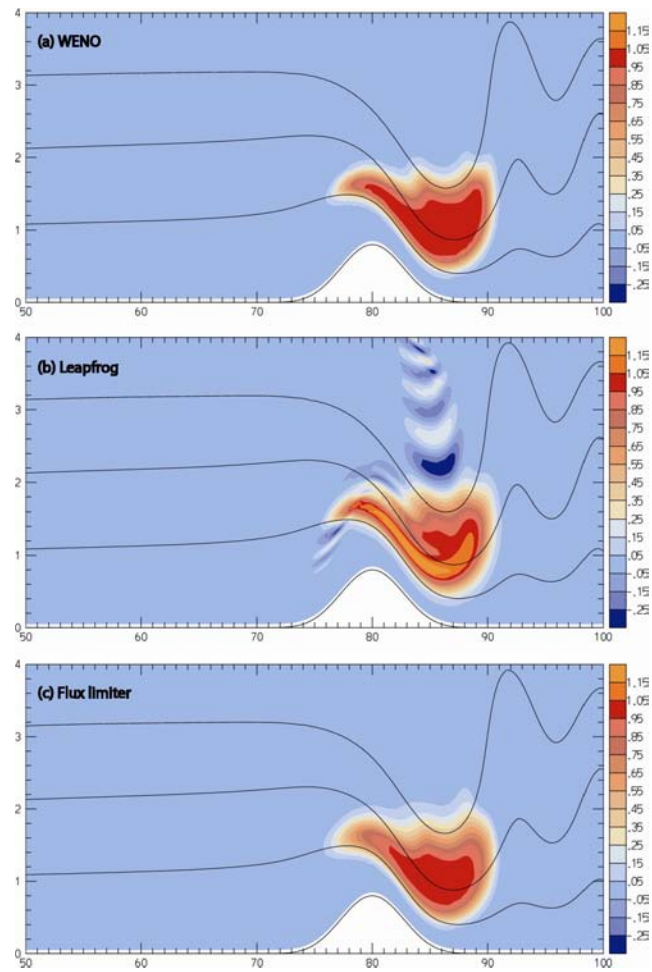


Figure 6. Isentropes and the passive tracer (color fill) for (a) WENO method is used for the advection, (b) leapfrog time, centered 4th-order spatial difference, and (c) a flux limiter method proposed by LeVeque.

IMPACT/APPLICATIONS

COAMPS is the Navy's operational mesoscale NWP system and is recognized as the key model component driving a variety of DoD tactical decision aids. Accurate mesoscale prediction is considered an indispensable capability for defense and civilian applications. Skillful COAMPS predictions at resolutions less than 1 km will establish new capabilities for the support of the warfighter and Sea Power 21. Operational difficulties with weapon systems such as the Joint Standoff Weapon (JSOW) have been documented in regions with fine-scale topography due to low-level wind shear and turbulence. Improved high-resolution predictive capabilities will help to mitigate these problems and introduce potentially significant cost saving measures for the operational application of JSOW. The capability to predict the atmosphere at very high resolution will further the Navy sea strike and sea shield operations, provide improved representation of aerosol transport, and will lead to tactical model improvements. Applications of COAMPS at resolutions less than 1 km will establish important direction for the development of the Navy's next generation microscale prediction system. Emergency response capabilities and Homeland Security issues within the DoD and elsewhere, such as LLNL, will be enhanced with the new modeling capability.

TRANSITIONS

The next generation COAMPS system will transition to 6.4 projects within PE 0603207N (SPAWAR, PMW-180) that focus on the transition COAMPS to FNMOC.

RELATED PROJECTS

COAMPS will be used in related 6.1 projects within PE 0601153N that include studies of air-ocean coupling, boundary layer studies, and topographic flows and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components (QC, analysis, initialization, and forecast model) of COAMPS. .

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